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THE PRECISION IMAGING SYSTEM (PIMS) CONCEPT

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NOVEMBER 1989

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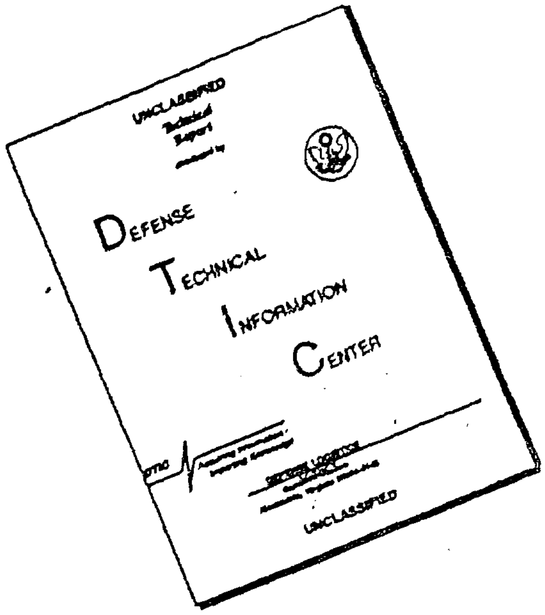

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The Precision Imaging System Concept (PIMS) is intended to increase the accuracy of direct-fire gun aiming systems, and simultaneously decrease the complexity and error associated with existing sighting systems. This system has the potential of simplifying the gunner task and reducing training requirements. In addition, this system has the potential to be extended to become the prime sensor for autotracking, passive ranging, image enhancement and surveillance C^3I systems.

This report reviews the theory of operation, the design of the optical subsystems, the high-speed image capture subsystem, the sight picùtre display subsystem, and the proof of principle tests of the PIMS concept. In addition, critical aspects of the technology and production base relevant to a fiedable system and extended applications are discussed.

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I. INTRODUCTION

The sighting systems of tank guns in use today rely on numerous mechanical linkages to perform the laying of the gun on the target. Inaccuracies in calibration, errors due to mechanical backlash and wear, thermal expansion and contraction of the system structure, and differences in dynamic response of various system components all compound to reduce accuracy in the aiming system. In addition, the flexure of the gun tube itself can account for major deviations from the gun-line aim point. The Precision Aim Technique (PAT) algorithm[1] has been shown to reduce the latter form of errors to manageable limits, and has been incorporated as an integral element into the Precision Imaging System (PIMS) concept. The former sources of inaccuracy are best eliminated by the fundamental basis of the PIMS concept: rather than acquiring the sight picture from a mechanical system coupled remotely to the gun tube, acquire the sight picture at the muzzle of the gun tube itself, thus eliminating all mechanical linkages. The PAT device is used to tell a sophisticated image acquisition system the exact time to "strobe" the scene and present the image to the gunner. In this way, the exact gun-line aim point at the time the round will leave the muzzle may be determined with none of the aforementioned inaccuracies. In essence, complexity is reduced through sophistication and simplicity[2]

The PIMS concept is an outgrowth of two Ballistic Research Laboratory (BRL) In-House Laboratory Independent Research (ILIR) Programs namely, "Image Stabilized Muzzle Sight" and "Real-Time Digital Image Processing." The results of these programs, the PIMS concept, was incorporated into the 6.2 mission program, "Tank Gun Accuracy", in fiscal years 1985 and 1986. It was determined that a system consisting of a digital camera, display system, control system and remote optics mounted on the muzzle of a gun can be suitably synchronized to the motion of the gun to provide a stable sight picture. The system exploits the PAT by referencing the sight picture to the predicted projectile exit, providing the sight picture at the desired tube condition for projectile launch.

The following is an overview covering the theory of operation, the design of the optical subsystems, the high-speed image capture subsystems and the sight picture display subsystems of the PIMS concept. In addition, critical aspects of the technology and production base relevant to a fieldable system and extended applications are discussed.

II. THEORY OF OPERATION

The theory of operation of the PIMS is based on this observation by Sissom[3]: "Indications are that use of a muzzle sight will reduce by about one-half the observed day-to-day variation in jump." Jump, for the purpose of this report, is defined as "the angular difference between a reference line established through the gun bore before firing and the effective line of departure of the projectile as it leaves the weapon upon firing."[4] Figure 1 illustrates this concept of jump when a muzzle bore sight is used.

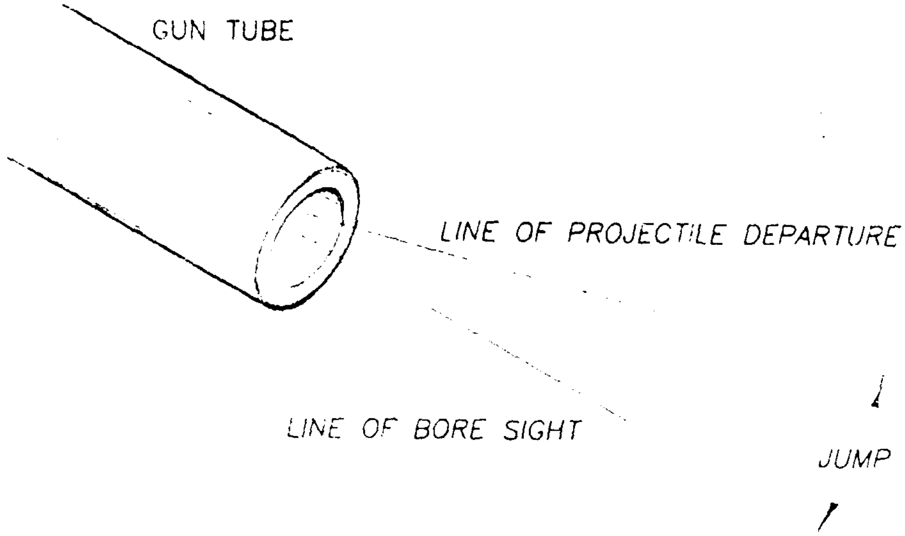


Figure 1. The Concept of Jump

There are two types of jump, 1) constant or aeroballistic jump which is a function of the specific projectile/gun system design and its dynamic response[5], and 2) variable jump which is the change of the projectile/gun system dynamic response to changing boundary conditions and environment including shifts in the pointing direction of the sight with respect to the gun tube at both the time of laying the gun and time of projectile exit. It is the variable jump that is addressed by both PAT[6] and PIMS.

A. Aiming From the Muzzle

The primary principle of operation of the PIMS is to aim from the muzzle of the gun or that portion of the gun near the muzzle that establishes the boresight axis. This position is believed to be within several calibers of the muzzle. Figure 2 shows the general arrangement for the PIMS sight[7]. The sight image is obtained by a simple telescope (1) mounted on or near the muzzle of the gun (2) then transmitted by means of a coherent fiberoptic bundle (3) to a digital electrooptical sense head (4) located somewhere in the turret. This sensor is controlled by the System Controller (5) which also controls a reticle generator (6), a target image buffer (7), a refresh buffer (8) and a display (9). The controller uses various inputs from the vehicle fire control system (10) and PAT system (11) to control the reticle, camera

framing and sight display and can provide data to the fire control system for such things as system status, input for PAT and ranging.

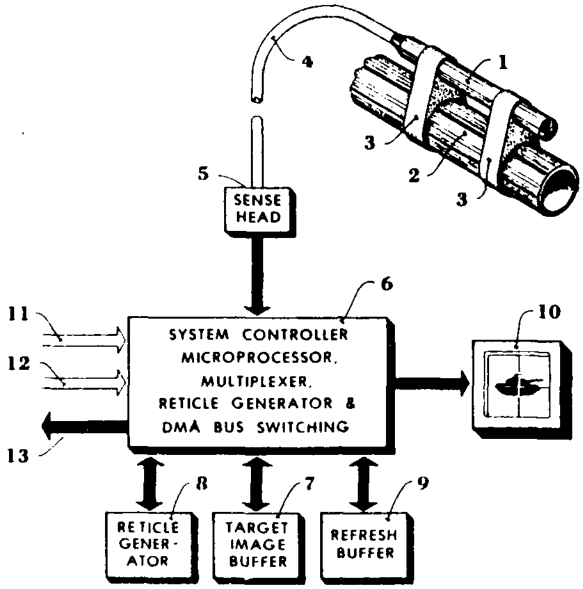
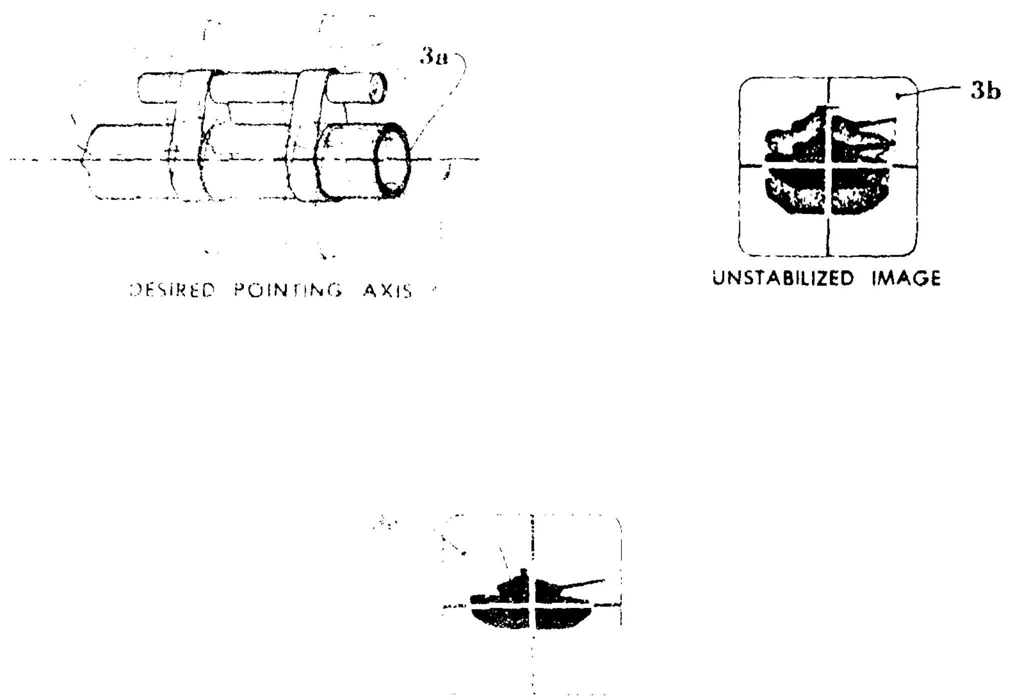


Figure 2. PIMS Sight

B. Synchronizing Target Image to Gun Motion

The controller uses the input from the PAT system to "strobe" the target image buffer and update the refresh buffer. The target image buffer consists of two memory units each capable of storing one frame of the sense head output. These memory units store alternate frames of the image in "ping-pong" fashion at the same high rate as the sense head (400 to 600 frames per second). When the controller calls for an image, the image in the memory unit that is not reading the sense head output is written into the refresh buffer. The image in the refresh buffer is displayed on the display device at nominal video frame rates (30 to 60 frames per second). The muzzle motion shown in Figure 3(a) results in the unstabilized target image illustrated in Figure 3(b). By appropriate use of the PAT system output, a stabilized target image (Figure 3(c)) is obtained when the muzzle is pointing along the desired gun-aim axis. The gunner moves the gun to obtain the desired sight picture, that is, the relative positions of the reticle and target image.[7] The "ping-pong" memory arrangement allows the image data to be available for other uses such as autotracking, image enhancement, lead determination and muzzle motion detection for PAT. For a sight system that does not provide image data to other subsystems, a much simpler buffer system can be used. The system used for demonstration of principle is discussed in Section IV.



[illegible] IMAGE

[illegible] Sight Picture Synchronization

Synchronizing Reticle Position to Vehicle/Target Motion

[illegible] located on the screen at a predetermined [illegible] geometry of the system and the [illegible] relationship of the number of display [illegible] Based on the calculated correction [illegible] can be electronically shifted to [illegible] vehicle [illegible], and aeroballistic jump. [illegible] not have to compensate for vehicle's [illegible] centering the reticle on the desired [illegible] the amount of judgement that [illegible] required to become proficient.

[illegible] OPTICAL SUBSYSTEM

[illegible] consists of three major [illegible] telescope, a long coherent fiberoptic bundle [illegible] Figure [illegible] shows the system breadboard [illegible] survivability tests.

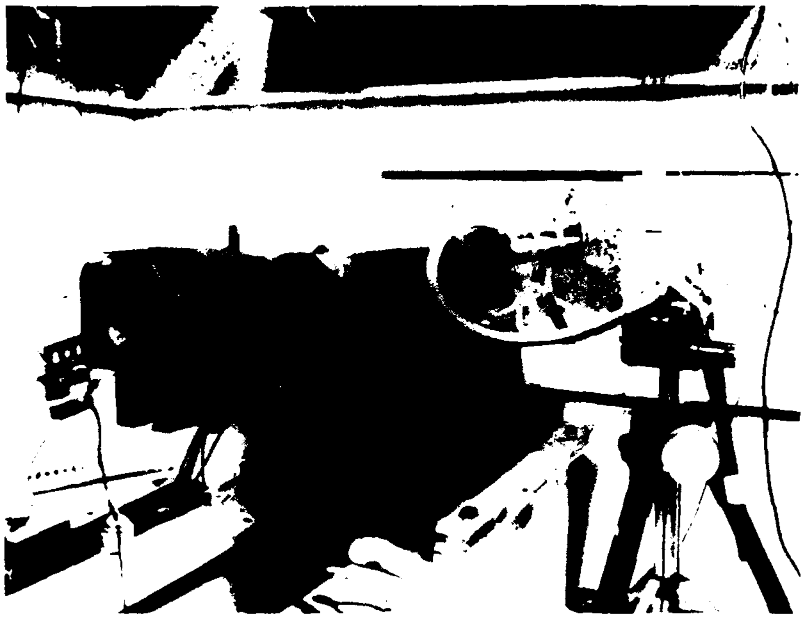


Figure 4. Breadboard System for Survivability Tests

A. Muzzle Environment

Of all the requirements that the optics system must meet, surviving the environment at the muzzle of the gun is the most difficult to achieve. This environment can be divided into two categories, 1) non-firing and 2) firing.

1. **Non-Firing Environment.** The optics that are exposed along the length of the gun tube must survive the nominal battlefield environment and the vehicle road environment. By mounting only the solid optic elements of the system exterior to the vehicle, the effects from electromagnetic interference are minimized by taking advantage of the shielding provided by the armor. Since the exposed optics are purely passive and contain no electronically active elements, they are not affected by electronic counter-measures. Infrared (IR) radiation countermeasures are effectively defeated through the natural IR impedance of the system and cause only momentary loss of target image without permanent damage to the detector system. It should be noted that the detectors used in this system are solid state devices and do not contain delicate photocathodes which are highly sensitive to both illumination and shock and vibration overloads. The effects can be further minimized by appropriate antiblooming circuitry in the sensing system.

The gunner is completely isolated by the system from direct visual contact to IR radiation and the potential retinal damage that it may cause. Similarly, Ultraviolet (UV) radiation is isolated from the gunner by the system. It should be noted that IR radiation signatures from potential targets can be observed through the same optics by altering the coupling to detectors in the sensing system and introducing image intensification. This capability has the potential to provide both normal visual and FLIR imagery through the same sighting optics. These additions can be made in such a

manner so as not to cause emissions back through the system which would cause detection. The glass components survive quite well under conditions of thermoblast and EMP. Survivability to artillery and small arms fire is greatly enhanced by redundant external systems, readily achieved by providing two sets of external optics (one on each side of the tube). Figure 5 shows a nominal road acceleration environment for the M1 Tank.

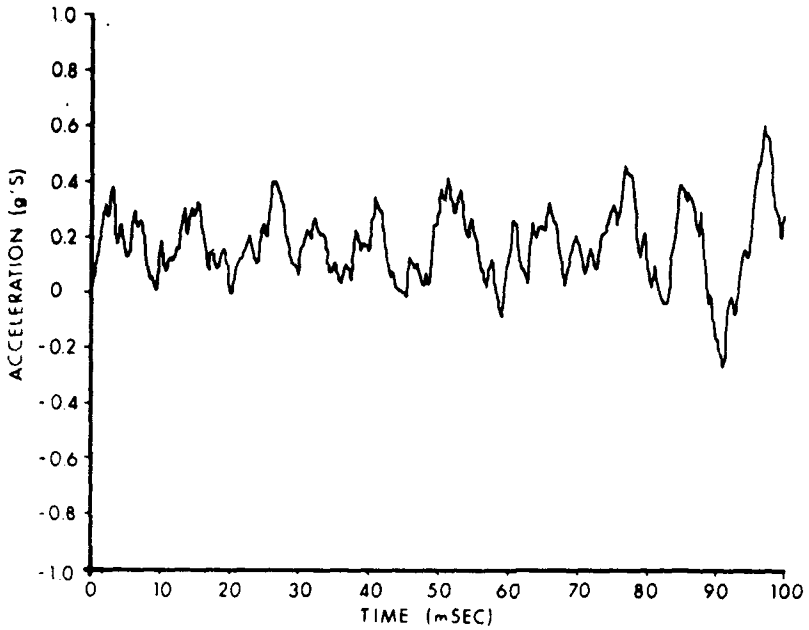


Figure 5. (U) Typical Road Environment for the M1 Tank

2. <u>**Firing Environment.**</u> The non-firing environment can be readily determined for a given vehicle system and there are well defined design techniques available to deal with the problems encountered. However, the firing environment at the muzzle is somewhat less determinant and the design techniques to deal with the problems are not well defined. From an engineering standpoint, the solution to the problems encountered become more artful than scientific.

The environment at the muzzle contains five principal elements: blast, gun system motion, flash, thermodynamic loads, strain waves. Blast and gun system motion can be adequately addressed through normal design techniques of dynamic systems. Flash is primarily addressed in the design of the sight detection system and will be discussed later. Strong thermal gradients require that the telescope incorporate self-thermal compensation to maintain focus and alignment. This is discussed in Section III.B. The primary design problem is to protect the optics and electronics from the strain wave environment generated on the surface of high velocity guns.

Figure 6 shows typical muzzle accelerations during firing for the M256 120-MM Tank Gun.

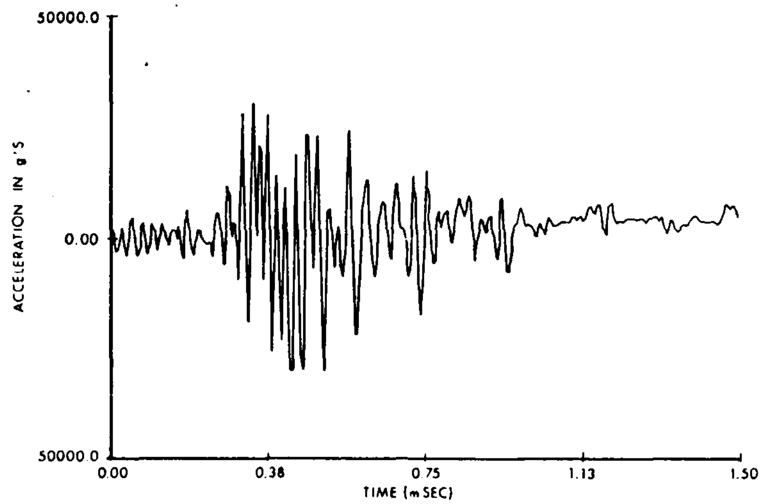


Figure 6. Typical Muzzle Acceleration During Firing

The problem of protecting optics from this environment is the same as the problem of making accelerometer measurements at the muzzle[8]. The optics and accompanying mounting structure must form a mechanical filter which, through a combination of reflection, dispersion and attenuation, isolates the optics from the strain waves. The amount of isolation that can be achieved is sufficient for solid optics but is not sufficient for solid state electronics. Even though structural survivability can be achieved, electronic survivability is difficult to attain. The piezoelectric nature of integrated circuitry is extremely difficult to protect from electronically damaging transients caused by the strain wave environment.

The problems of temperature control, blast protection, vibration and shock, and physical size of the image capture device all contraindicate the muzzle as the desirable location. The advantage of a single package of compact dimensions with minimum optical components is the major argument in favor of the muzzle location. While it may be technically feasible to develop a custom large-scale integrated circuit and hybrid assembly to contain the entire image acquisition system, survival of the system precludes the muzzle as the chosen system location. In order to locate the image acquisition system remotely from the muzzle, the image has to be "piped" non-electronically to the remote location. A long, coherent fiberoptic bundle, was best suited to this application and is discussed further in Section III.C.

B. Sight Telescope and Optical System Errors

The telescope (Figure 7) has a 75-mm focal length at f2.1, providing approximately 3X magnification. The high speed sensor has a resolution of 256 X 256, with pixels on 40 micron centers, yielding an aperture of 136.53 angular mils and a resolution of 0.266 angular mils. The system can resolve 26cm at 1km, equivalent to a pointing error of $\pm$ 0.133 angular mils.

Increases in either the sensor resolution or the telescope magnification will improve the resolution of the system as a whole.

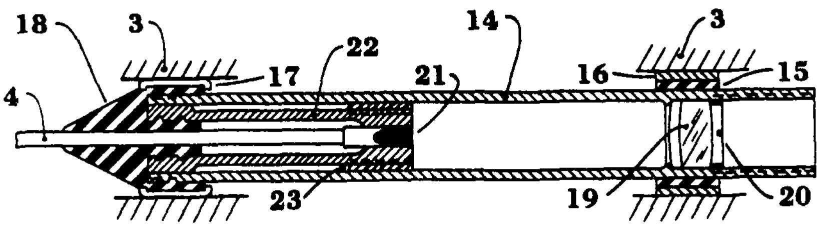


Figure 7. Sighting Telescope

1. **Temperature Compensation.** Errors will occur when the length of the telescope changes due to temperature variations. This error is easily counteracted by mounting the image plane element (in this case the end of the fiberoptic bundle (21) on a compensation tube (22) made of metal with a different thermal expansion coefficient than that of the telescope housing (14), which carries the object lens assembly (19). For example, use a steel telescope tube with a linear expansion coefficient of 0.125x10-4/°C for the housing and a brass tube with a linear expansion coefficient of 0.218x10E-4/°C for the compensator. The compensator is then attached to the housing and lens such that the expansion of the two tubes counteract each other. Then:

$$Lt/Lc = Cc/Ct = 1.744 \qquad (1)$$
$$Lt = Lc + Fl; \text{ and} \qquad (2)$$
$$Lt = 2.34Fl; \qquad (3)$$

where Lt = Length of the telescope;
Lc = Length of compensation tube;
Ct = Thermal expansion coefficient for telescope housing;
Cc = Thermal expansion coefficient for compensation tube; and
Fl = Focal Length of telescope.

If the telescope is designed with a compensator tube and housing that obey these relationships, this source of error is practically eliminated.

2. **Shock Isolation.** Another source of error is misalignment or damage to the telescope due to strain waves coupled into the telescope from the gun by the mounting system. The telescope shown in Figure 7 has the elements 15, 16, 17, and 18 which are designed to form an integral mechanical filter to reduce the transmission of high frequency components of shock and vibration to the

telescope. A typical mechanical filter cutoff frequency is 1/-kHz. Road tests done at APG on the M1 tank indicate a maximum acceleration of 25-50 m/sec^2 on bumps, and an average maximum of $6m/sec^2$ over a frequency regime of 2.5 to 25 Hertz. If d is the relative displacement in meters between one end of the telescope and the gun tube, G is the maximum acceleration in m/sec^2, and f is the mechanical filter cutoff frequency in cycles/sec, then:

$$d = G/(2*pi*f)**2. \tag{4}$$

The relative maximum error in angular mils, ED is given by

$$ED = 2000000d/Lm \tag{5}$$

where Lm is the length in meters between telescope attachment points. For practical purposes, this may be approximated by the focal length. For a 75-mm focal length telescope, the maximum relative pointing error can be expected to be on the order of 0.034 angular mils. A filter cutoff frequency of 3kHz reduces the error to 0.004 angular mils.

C. Coherent Fiber Optics

Once the decision is made to place the electronics in a location remote from the muzzle, an optical device is required for transmitting the image from the telescope to the sensor. The device chosen is the fiberoptic coherent bundle, also called an imagescope.

1. Imagescope Functioning. A single optical fiber cannot pass an image, but rather passes a light level proportional to that exposed to its input end. If we view an image as an array of dots of different intensities, it is conceptually possible to connect a single optic fiber to each dot or pixel, of the input image to its corresponding pixel in the output image and thus relay the input image to the output end of the imagescope. In reality, the size and spacing of each fiber is considerably smaller than a pixel hence, alignment is not critical and higher resolutions are possible. In order to prevent crosstalk between adjacent fibers, causing image blurring, each fiber is clad with a glass of lower index of refraction. Since no light is transmitted in the cladding, this geometry results in an approximately 50% reduction in the effective cross-sectional area of transmission for the imagescope. The following calculations take into account this reduction of transmission area. Figure 8 shows an imagescope and the image of a standard target.

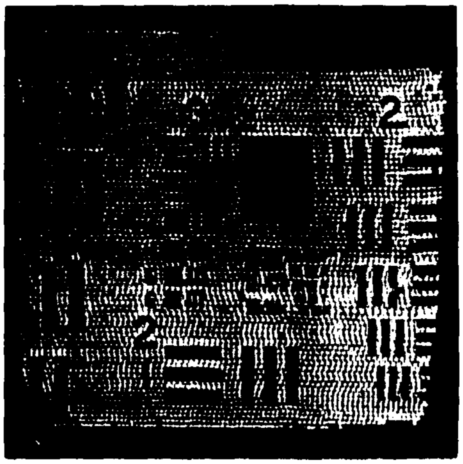


Figure 8. Imagescope Image of Standard Target

2. Typical Optical Characteristics. Standard industrial imagescopes are fabricated from conventional glasses and can exhibit losses from 1000 to 2000 dB/km. Since the (most desirable) location for the image capture device is inside the vehicle, the typical length of the imagescope would be 12 meters. This represents a loss of 12 to 24 dB or equivalently a 3% to 0.2% transmission of light; this is inadequate for most conditions. This situation can be alleviated by either using an image intensifier or fused silica fiberoptics. Due to their sensitivity to vibration and their relatively short useful life, approximately 1000 hrs, image intensifiers are not considered here. Since the coherent fused silica imagescope has a high potential survivability in the gun environment, it was developed under contract for the BRL[9,10].

3. Enhanced Performance. The high-purity fused silica fiber material minimizes the transmission losses of the individual fibers, increasing both the signal strength and the ability to transmit wavelengths beyond the visible. Either ultraviolet or infrared light may be transmitted with the visible signal, but not both. Ultraviolet transmission is limited by the presence of dissolved oxygen; infrared transmission is restricted by water molecules in the fibers. It is not currently feasible to eliminate both contaminants, although this constraint may lessen in the future.

In use, one end of the fiberscope is placed at the image plane of the telescope, and the other brought into the vehicle to the location of the image acquisition subsystem. Only the ends of the fiberscope where the bundles were cemented together have a fixed shape; the remainder of the bundle consists of loose strands, of 60-micron square multifiber (6 x 6 fibers). This loose mass of fibers may be shaped into a ribbon, round section or whatever is needed for convenient packaging.

There are several mechanical constraints that the tactical vehicle places on the imagescope. Military standards dictate an operating range of -60°F to +450°F, with humidities from 0 to 100%, condensing. The system must withstand continuous exposure to weather and sunlight as well as intermittent exposure to chemical agents. Expected vibration levels are 3G at frequencies from 1 to 600 Hz with repeated shocks of 300 G, 15 millisecond duration half-sine. The gun recoil, which is a flexure shock represents a 13 inch displacement in 250 milliseconds, half-sine. Section VII.B discusses the results of the optics survivability tests.

D. Digital Sensor

There are three major components of the optical subsystem: a telescope, an imagescope and a high-speed sensor. The telescope and the imagescope capture an image and make it available to the digital sensor by some optical transfer mechanism. This mechanism provides the coupling of the image to the sight picture acquisition system (see Figure 9).

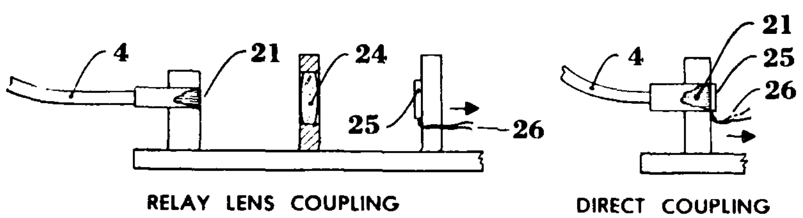


Figure 9. Optical Couplers

Since the operating environment of the sensor is subject to severe vibration and shock, vidicons and other vacuum tube type image sensors are not viable. A solid state type of sensor is indicated.

1. Gun Environment

The gun tube is not a rigid body; it bends as a result of shock and vibration, causing it to oscillate with a specific set of frequencies. This oscillation implies that at any random time, the muzzle is not necessarily pointing at the nominal aim point. This point, defined by the PAT system as the zero-crossing point, is the optimal time for the sight picture to be taken and the round to exit the muzzle. The angular slew rates at these crossing points determine the frame exposure time for 'strobing' the scene in order to obtain an image free of motion-induced blurring.

As a rule of thumb, motion-induced blur is negligible if the scene moves one tenth of a pixel or less during the acquisition time of the image. The necessary time and framing rate may be calculated thus:

$$Ta = Ap/(10Rd) \text{ sec and} \tag{6}$$
$$Fr = 1/Ts \text{ frames/sec} \tag{7}$$

where

Ta = acquisition time in sec;
Ap = aperture angle per pixel in mils;
Rd = rate of angular displacement in mil/sec; and
Fr = frame rate in frames/sec or Hz

Measurements taken at APG indicate that for the M1 tank, the worst case (bump) displacements correspond to a slew rate (Rd) of 53 mil/sec and an aperture angle per pixel (Ap) of 0.533 angular mil. These data produce a shutter time of.00101 sec and a frame rate of 994 Hz. In comparison, average displacements correspond to a slew rate of 13.25 mil/sec, which requires a shutter time of .00403 sec and a frame rate of 248 Hz. Based on existing data from the PAT program, a frame rate of 250 Hz will suffice for 50% of the firing opportunities, 400 Hz for 94.5% and 600 Hz for 99.2%. These estimates are based on limited data from one system and are to be construed as such; however, they indicate that the emerging state of the art in digital photodiode array technology is sufficient to provide a viable sensor for a PIMS system.

Since the oscillation of the gun tube is unpredictable, it does not provide a regular zero-crossing period which will establish a consistent sensor framing rate. The PAT system provides a pulse at the time of zero crossing; it is at this point (or very close to it) that we want to acquire a sight picture. One way to accomplish this is to let the sensor free run so that a complete frame of video data is acquired each time the sight picture changes by 1/10 of a pixel. If the PAT system provides its pulse at a time when the sight picture is within 1/10 of a pixel of zero crossing, an acceptable picture will be acquired. Fortunately, the framing rate required to capture this picture is the same rate used to eliminate motion-induced blur. Running at this frame rate guarantees minimum blur and maximum exposure time for each frame. The camera system can be enhanced by using an electrooptical shutter in addition to the camera. Operating the shutter at a higher rate than the camera boosts overall system speed; however, sensitivity at low light levels is degraded by lower signal-to-noise ratios.

2. **Current Technology.** At this writing, only one vendor offers an experimental solid state sensor capable of high frame rates and reasonable intrascene dynamic range (300:1). This sensor (Figure 10) consists of an array of 256 X 256 silicon photodiodes with ten CCD shift registers, providing eight video output taps at frequencies from 3 to 8 MHz. With these pixel clock rates, frame rates from 360 to 960 frames/second are possible.

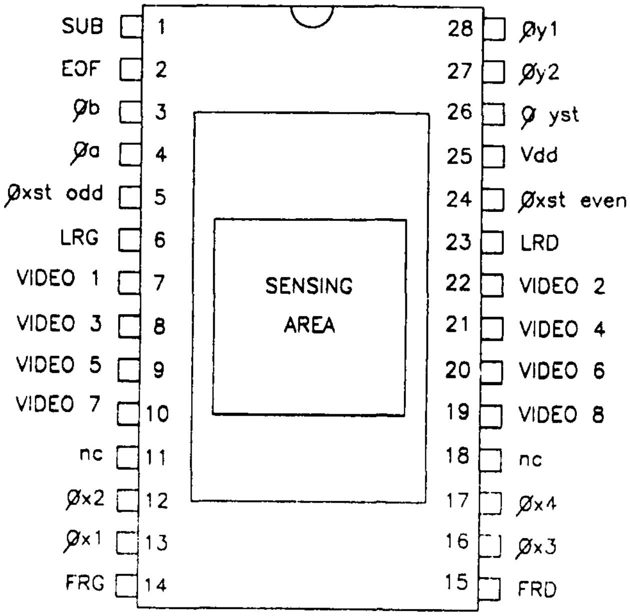


Figure 10. High Speed Sensor

The saturation light intensity is approximately 3 erg/cm^2., and the equivalent noise exposure is .001 erg/cm^2 at 570 nm. The noise equivalent exposure is given at 70°F and may be reduced by cooling the sensor. For armored vehicle and other military applications where cryogenic cooling becomes a logistical and technical hindrance, 80% of the available dynamic range can be achieved by thermoelectric cooling to 32°F. The spectral response of the sensor is essentially that of a p-n junction photodiode, and is smooth from 0.2 to 1.1 microns. The intrascene dynamic range (defined as minimum saturation divided by RMS noise) is greater than 300:1 and can be expected to ultimately reach values greater than 1000:1 with sensor cooling and proper design of output amplifier stages to match sensor characteristics more exactly.

The multiple video output scheme of this sensor is clearly superior to conventional CCD single serial output types for a number of reasons. In order to attain the frame rate of 600 frames per second, a pixel clock rate of 64 MHz would be required. Acquiring video data at this rate represents a formidable problem, and requires delicate and expensive instrumentation to do so. Moreover, since noise on a signal is usually proportional to the square root of the signal bandwidth, the higher frequencies introduce a factor of 3.6 greater noise on the video signal. This in turn drops the effective intrascene dynamic range from 300:1 to 83:1, unless special filtering and noise reduction techniques are used.

Another major drawback of attempting to operate a conventional sensor at higher frame rates is the matter of charge mobility. In a CCD sensor, small packets of charge are shifted through numerous stages on their way to the output stage. The implicit assumption is that the charge carrier mobility in the semiconductor is high enough to allow the packet to completely move to the next stage during one shift of the register. As the frequency rises above 10 MHz, this becomes a poor assumption. Since the packets cannot completely move between stages. The observable result is a reduction in intrascene

dynamic range and contrast. As speeds increase further, contrast approaches zero. By using multiple outputs, the data rate at each output is held at a reasonable value, and the composite data rate rises with the number of output taps.

3. Sensor Geometry. The high speed sensor is an array of photodiodes, 256 rows of 256 columns each. The geometry of the high speed sensor (Figure 11) is divided into 256 rows of 256 columns of photodiodes. Each photodiode is connected to a MOS access switch which serves to gate the charge accumulated on the photodiode to a video line. The MOS switches also act as additional capacitance and provide additional charge storage for increased dynamic range. Each row is divided into eight groups of 32 pixels (columns), one group per video line.

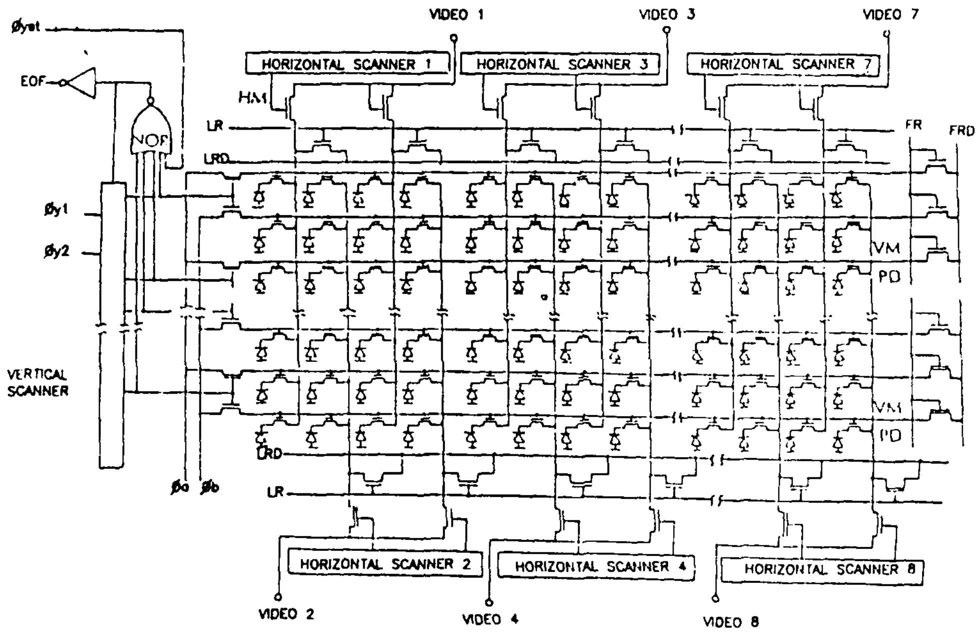


Figure 11. Sensor Geometry

The combination of the vertical scanner and one of the two clock phases (A or B) select a row to scan. The eight horizontal scanners then switch each of the 32 pixels in each group onto the video lines 1 to 8. At the first pixel clock pulse, pixels 1,2, 65, 66, 129, 130, 193 and 194 are output to the video lines. At the second pulse, pixels 3, 4, 67, 68, 131, 132, 195 and 196 are sent. This continues until the last set of pixels (63, 64, 127, 128, 255 and 256) is output to the eight video lines. Each shift of the vertical scanner actually selects two rows which are determined by clocks A and B. The sensor timing is shown in Figure 12 below.

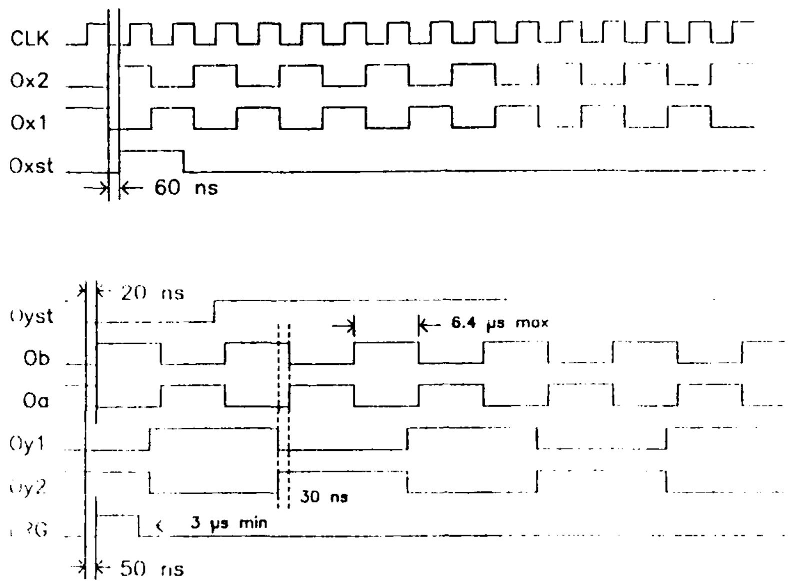


Figure 12. Sensor Clock Signal Timing

In addition, the sensor is fitted with a frame reset feature that allows all photodiodes to be "grounded out" so that the accumulation of an image does not begin until this reset is released. The primary disadvantage of using this feature is that the signal generated by incident light and that from noise is continualy integrated until readout, so that the rows read out last may have significantly more signal and noise in them than those read out first. If readout is kept at a constant frame rate, then all pixels are read out with the same integration interval and this effect does not contribute error.

IV. THE IMAGE CAPTURE SUBSYSTEM

The timing relationships required by the sensor are shown in Figure 12. Complementary clock signal crossings are at 10% amplitude or less. The logic to generate these signals is shown in Figure 13. The level translation stages and bead inductors necessary to produce the correct bias voltages for the sensor and zero crossings are not shown for sake of simplicity.

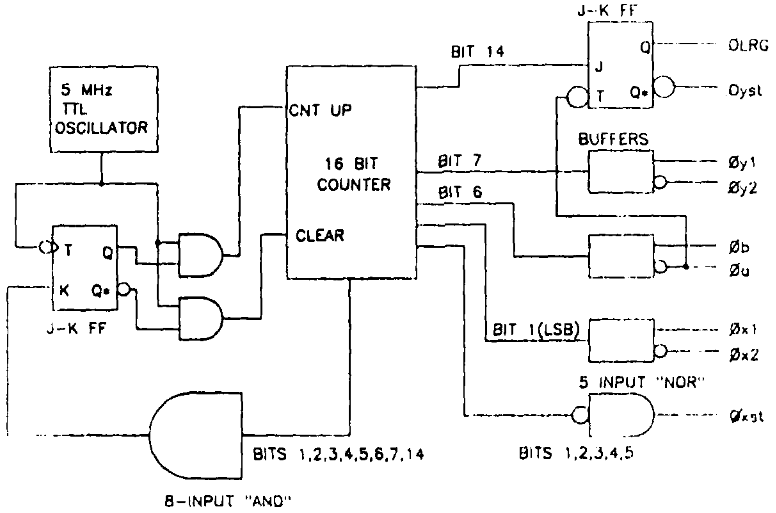


Figure 13. Scan Clock Generation Logic

The implementation of the clock logic and that logic required to generate the correct timing signals for the integrating amplifiers and ADC's form a state machine of the Moore type, with the output levels only dependent on the state the machine is in. If this implemented in field-programmable logic sequencers, this represents a single 20-pin integrated circuit versus 12 or more discrete (SSI) integrated circuits if done in traditional logic design.

The output signal of the sensor consists of charge packets, one per pixel. At saturation, the maximum charge of one of these packets is 5.7-pC.

A. Analog to Digital Conversion

In order to condition the sensor output signals and convert them to digital form for frame storage three functions must be performed by the camera subsystem: charge integration, analog-to-digital conversion and timing control. A block diagram is shown in Figure 14. The output from this subsystem is eight channels of 8-bit wide digital data with status information bits which indicate new pixel data, new frame and new line.

Due to the tiny charges expected, the charge integrating amplifier must be made from ultra-low offset, low leakage operational amplifiers. The integrating capacitor in the feedback loop must also have low leakage and small capacitance in order to get a useful charge-to-voltage conversion. In addition, the capacitor must be discharged after integrating the charge on each pixel before the next pixel is done. In order to do this, a DMOS FET analog switch is used both for the integrating capacitor and the discharging switch. In its open position, its source to drain capacitance is approximately 2-3 pF. With this value, an input charge of 5.7 pC represents an output of 1.9 to 2.8 volts from the integrator. An adjustable gain amplifier after the integrator serves to balance the channel to the same overall gain as the other seven channels in the bank. The leakage current of the analog switch in the "off" condition is typically 0.1 to 1 nA. If we

compare this to the current output of the sensor which is 95 nA to 28.5 μA, we see that the leakage is on the order of 1.05% worst case. With judicious selection of the analog switch, leakage is 0.1% compared to 0.4%, the size of a digitized bit assuming 8-bit converters.

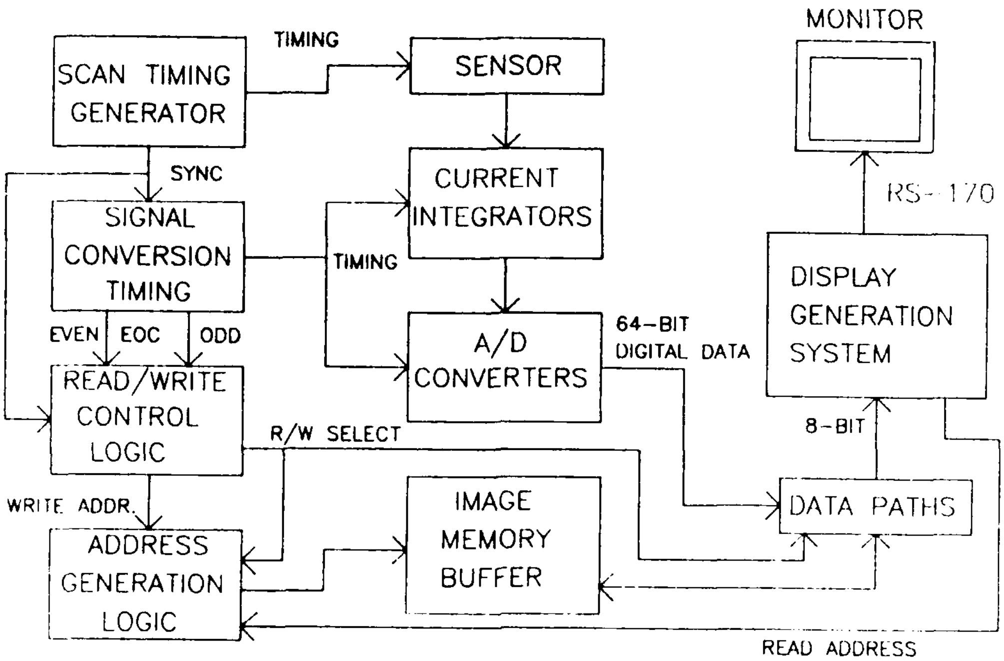


Figure 14. Camera System Block Diagram

An alternate and simpler method of analog signal conditioning is to use the operational amplifier as a current-to-voltage converter. In this case, if the value of the feedback resistor is set to 35-KΩ the output voltage range is 3 millivolts to 1 volt. The selection of which of these will prove to be the best remains to be determined experimentally. In either case, once the charge packets have been converted to voltages, flash CMOS analog-to-digital converters capable of 10 million samples per second convert the data to 8-bit digital form for storage in a frame buffer system.

B. Frame Buffer

In order to produce a flicker-free picture, common television transmissions present 30 frames of images per second in the form of two half-frames, one containing the even numbered lines on the screen, and the other the odd numbered lines. These half-frames are interlaced so that one complete frame is shown in 1/30 of a second, but the screen is refreshed with a new picture every 1/60 of a second. This 60 picture/sec rate places the frame rate above the nominal flicker fusion rate of the eye, which is approximately 40 picture/sec. In the PIMS system, frames are scanned by the sensor at a rate of 250 Hz or more, with PAT zero crossings at frequencies from 0 Hz (when the gun tube is at rest) to 25 Hz. In order to present the gunner a flicker free view, it is then necessary to buffer the frame rates so the video format is similar to common (e.g., RS-170) video standards. An additional advantage

of doing this is the ability to use many common commercial video instruments in the system, reducing both cost and development time.

The frame buffer (Figure 15) as conceived for the PIMS system is a static random access memory system, single ported, based on (8k x 8 CMOS RAM chips) with a 100-ns access time. The typical operating power of these chips is 200 mW, with single 5-volt supply operation. Conceptually, the frame buffer is arranged as 256 X 256 memory locations of eight bits each. Each memory location corresponds to a single pixel both on the sensor and on the display screen, and can represent one of 256 levels of intensity between black and white. The present PIMS system is black and white only, although further sensor and electronics development could quite easily make color possible).

It would seem that the frame buffer should be dual-ported, since it is filled from one source and dumped to another "simultaneously". In reality, since a frame time is on the order of 1/500 of a second or less at the sensor, and the display time of that frame on the screen in front of the gunner is 1/60 of a second, it is possible to drop out 12% of one of the display frames and still be within the flicker fusion rate of the eye. During this dropout time, the frame buffer is connected to the sensor to update the stored image and then reconnected to the display system.

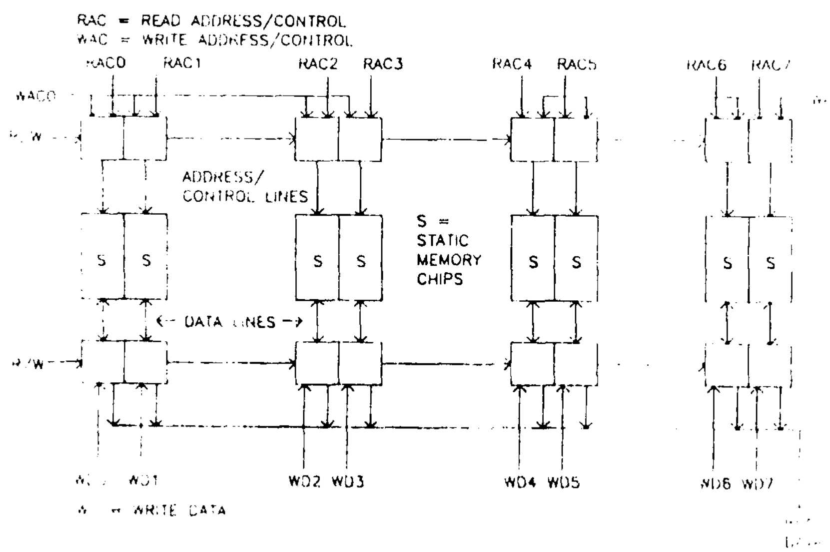


Figure 15. PIMS Frame Buffer

The two distinct modes of operation of the frame buffer (updating and display) represent two different types of data access. In display mode, one memory value (pixel) is output at a time, whereas in the updating mode, eight memory values (pixels) are simultaneously written on each cycle. This split operation is accomplished by having two distinct and separate memory address and control logic systems, and then using a multiplexing scheme to connect the appropriate one to the address lines of the frame buffer for each mode. In addition, since the memory data lines are common for both input and output, it is

data, these too are multiplexed. In the update mode when data is written from the ADC's to the memory, the buffer is arranged as eight separate buffers each 8192 locations long. Each of the eight channels of ADC data is written sequentially into locations in each chip, one channel per chip. For this operation, the address generator is little more than a simple 13-bit binary counter, commonly driving all eight chips' address lines in parallel.

V. THE DISPLAY SUBSYSTEM

In a conventional raster scan display system, there is a one-to-one correspondence between memory locations and pixels on the display screen. The most common way to number pixels is to start at the upper left corner of the screen and number from left to right, and top to bottom. For our resolution, this represents pixels numbered from 0 to 65535. The simplest way to visualize the memory space of the frame buffer is as a linear array of locations numbered the same as the display locations, so that the pixel number on the screen corresponds to that address in memory. It should be obvious that, given the nature of the update process, the sensor data is not written to the memory chips in such a way as to allow such a simple linear memory decoding process to be done. In order to make the address decoding easier to understand, Table 1 relates the video output with the portion of the sensor that it represents:

TABLE 1. OUTPUT/PIXEL LOCATION RELATIONSHIPS

Output line	For rows 1 to 256, the output represents:
Video 1	columns 1 to 63, odd pixels only
Video 2	columns 2 to 64, even pixels only
Video 3	columns 65 to 127, odd pixels only
Video 4	columns 66 to 128, even pixels only
Video 5	columns 129 to 191, odd pixels only
Video 6	columns 130 to 192, even pixels only
Video 7	columns 193 to 255, odd pixels only
Video 8	columns 194 to 256, even pixels only

A. Display Memory Coding/Decoding Process

Recalling that each of these video lines was written to a single memory chip, we see that, for each row in the picture the first 64 pixels are taken alternately from the two chips associated with Video 1 and Video 2 in interleaved fashion. The next 64 pixels in the row are taken in the same interleaved way from the second pair of chips and so on for the two remaining chip pairs. The treatment of the memory chips in pairs allows a decoding scheme to be more easily understood.

In order to address 16536 memory locations, a 16-bit address is needed. Bit 0, the least significant bit (LSB) of the address, is used to indicate which chip within a pair is selected. If the LSB is 0, the chips corresponding to the video lines for odd numbered pixels are chosen; if the LSB is 1, the even video chips are chosen. This is done simultaneously for

all four pairs of chips. Bits 1 through 5 contain the least significant five bits of the address for all eight chips in the buffer. The next two bits are used to select one of the four pairs of chips to be read. The last eight bits, bits 8 to 15, contain the most significant eight bits of the eight chips in the frame buffer. In this way, each chip is presented 13 address lines and two chip enable signals: one to provide the interleave and one to select the active pair. This arrangement happens to match the signals required by the static CMOS RAM chips chosen for the memory array. The readout of the correctly unscrambled pixel sequence requires minimal logic if the 16-bit address counter used to keep track of the logical pixel address on the screen. A graphic breakdown of the 16-bit address is shown in Table 2 below:

TABLE 2. 16-BIT MEMORY ADDRESS CODE

	MSB						16-Bit Address									LSB
POSITION	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

Bit	Function
0	Selects low (even) or high (odd) chip of chip pairs
1 - 5	Low 5 bits of address of location in chips (all 8)
6 - 7	Selects active chip pair, 00, 01, 10, or 11 (binary).
8 - 15	High 8 bits of address of location in chips (all 8)

B. Target Image Display

The display subsystem next converts the stored digital image to analog form, driving a conventional RS-170 video monitor. In order to meet RS-170 video standards, the horizontal frequency of the synchronization portion of the signal must be 15.75 kHz nominal, with the vertical frequency at 60 Hz. Horizontal blanking times on the order of 11 microseconds and vertical blanking times nominally equal to 18 horizontal lines (about 1.16 milliseconds) are the required standard. Due to the low resolution 256 X 256 image generated by the sensor, video bandwidths are less than 5 MHz. The composite video output contains the picture data, and blanking and sync information. The picture is written onto the screen starting at the upper left, scanning from left to right, and top to bottom.

For those unfamiliar with video terminology, a discussion of composite video is in order. The display monitor generates signals which sweep an electron beam across the screen to draw a line and up and down the screen to position subsequent lines. In order to generate a picture, the monitor must tell the sweep circuits two things: when to begin drawing a new frame and when to begin drawing each of the lines within a frame. These functions are controlled by the frame (or vertical) sync and line (or horizontal) sync. Additionally, the electron beam must be turned off as it moves from the bottom of the screen to the top and from the end of one line to the beginning of the

next. The signals corresponding to these functions are, respectively, the vertical and horizontal blanking.

Standard video voltage levels range from 0 to -1 V; this range is divided into 140 IRE units of about 7.14 mV each. Zero IRE corresponds to the blanking level. Sync level occurs at -40 IRE, well below the blanking level. Video picture information is obtained in the areas between reference black (0 to 20 IRE) and reference white (100 IRE). These levels are illustrated in Figure 16.

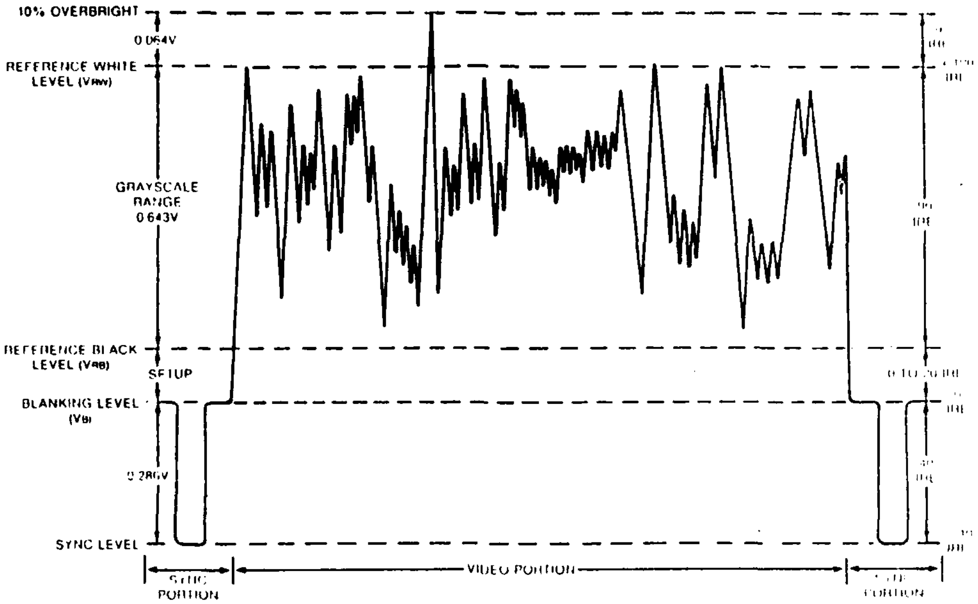


Figure 16. RS-170 Video Signals

The composite sync signal is the logical exclusive-OR of the horizontal and vertical sync signals. The composite blanking signal is the logical OR of the horizontal and vertical blanking signals. The superposition of the video, blanking and sync signals then forms the composite video signal and contains the minimum necessary information to generate a picture. This superposition is accomplished using an 8-bit composite video digital-to-analog converter module. This module's inputs are logic levels for video, data strobe, composite sync and blanking, and inputs to drive the output to reference white level and 10% overbright level. The latter is useful for superimposing white alphanumerics or graphic cross hairs over a video image. The output from this commercially available module drives an RS-170 video monitor directly. The timing logic necessary to produce the composite sync and blanking levels is driven from a common clock oscillator, as is the additional logic used to generate the primary memory readout addresses and control signals. The method used to generate the various blanking and sync signals requires some explanation.

The primary driving factors for the selection of display format are the horizontal frequency (15.75 kHz nominal) and the vertical frequency (60 Hz nominal). For a 256 X 256 pixel display, the timing generation logic is set to produce a picture of 310 pixels/line and 275 lines per picture. If we

number the pixels in a line from 0 to 309, the first 256 pixels of a line (0 to 255) represent the image data pixels. The horizontal blanking signal is generated for pixels 256 to 309. The horizontal sync pulse is asserted during pixels 263 to 285, which then defines pixels 256 to 262 as the "front porch" and pixels 286 to 309 as the "back porch" of the horizontal composite blanking/sync signal. The vertical section is much the same as the horizontal one. Lines 0 to 255 are the image lines, vertical blanking is asserted during lines 256 to 274, and vertical sync is asserted during lines 259 to 261. The horizontal and vertical blanking signals (asserted in the logical "low" state) are combined in an "OR" gate to form the composite blanking signal. The horizontal and vertical sync pulses are combined in an exclusive "OR" gate to form the composite sync signal. Both of these composite signals are used by the final digital-to-analog converter stage to superimpose the composite blanking/sync signal on the output video for a standard RS-170 monitor display.

C. Reticle Display

In order to aid the gunner in accurately placing the aim point, cross hairs indicating the nominal aim point are drawn on the screen with the 10% overbright level indicated previously. The telescope is pointed directly in a straight line path parallel to the axis of the gun tube. Since the round actually hits the target at a point lower than the straight line aim point, some correction of the cross hairs from exact screen center is necessary. The actual angular displacement from nominal aim point to the impact point, or supereleviation, is generated by the vehicle's fire control computer. This signal is utilized by the cursor generating logic to displace the cursor downwards on the screen to indicate the impact point of the round. Since the number of angular mils per pixel is a constant for the optical system, the computation of cross hair displacement is nearly trivial. Conceptually, what the gunner sees is a steady target picture with cross hairs indicating the point of impact. Gross movement of the gun tube is removed by the turret servosystems, while the gun tube oscillations are made unimportant by the PIMS system implementation of the PAT*concept. A portion of the logic in the PIMS system detects the zero-crossing and muzzle exit pulses issued by PAT as well as the command to fire the gun. If a fire command has been given, then the PIMS system will not acquire new sight pictures during the time that the muzzle flash is saturating the image sensor. This time duration is normally less than 15msec and will not appear on the display. The gunner will not see it in the sight; some visual indicator may have to be employed to avoid sensory contradiction.

D. Static Firing

A significant case is the static condition, when there is no vehicle movement and no gun tube oscillation. The gun is continuously at the zero-crossing point. In this case, the PIMS updates the frame buffer every 1/30 sec as long as the gun tube remains at rest at the zero-crossing point. This is implemented with a simple retriggerable monostable multivibrator and a logical AND gate. If zero crossing is true and the one-shot times out, the output pulse both triggers a frame update, and retriggers the one-shot.

VI. LIGHT LEVEL CONSIDERATIONS

Several other issues remain to be addressed in relation to the light levels required for the sensor and its operation in low light level conditions. In order to make maximum use of the intrascene dynamic range of the sensor, the brightest pixel in the image must be near the saturation level of the sensor (3 erg/cm^2 at 570 nm). A good rule of thumb is that in the visible, 1 Watt is approximately equivalent to 673 lumens. Since a Watt is 10E+07 erg/sec, and the exposure time of a frame is about 1/500 of a second, then to saturate the detector requires an illumination of about 9.3 lumens/ft^2. Recalling that the loss due to the f-stop of the telescope is about 78%, the scene illumination needs to be approximately 42 lumens/sq. ft. If we assume a loss of 55% in the imagescope, the final scene illumination is near 94 lumens/sq. ft., which corresponds to the illumination outdoors on a heavy overcast day. As dusk approaches, or on a rainy day when illumination levels fall to less than a few lumens/sq.ft, the contrast range in the image that the sensor displays will fall to less than 30:1. At a scene illumination of 0.2 lumens/ft^2, (mid twilight) the signal to noise ratio for the sensor will be 2, the useful limit of the detector.

A. Increased System Gain

If the PIMS system is to be used in lower light level conditions than described, or if a higher signal-to-noise ratio is needed at conventional twilight levels, there are several ways to achieve an increase in system gain.

1. Image Intensification. The image can be boosted by introducing a proximity focused diode image intensifier into the optical system. The typical gain of such a tube ranges from 5 to 40; the image transfer resolution is typically 40 line pairs/mm. If higher gains are needed, then microchannel plate electron multipliers may be built into the intensifier, resulting in gains of up to 20,000. The cost of this additional intensification is loss of resolution, dropping to about 22 line pairs/mm. It is possible to enlarge the primary image using either lenses or tapered imagescópes, intensify the enlarged image and then reduce the image size back to normal. Such a procedure will gain resolution by the enlargement factor at some loss of intensifying efficiency. Fabricating the tapers from the ultra-low loss fiber used for the long fiberscopes could be expected to reduce the losses in the taper considerably. Additional losses can be limited by restricting the number of lenses to those in telescope. All other optical transfers are made using direct fiberoptic coupling. Up to 25% could be cut in this way.

2. Thermoelectric Control Of Sensor. The sensor can be cooled to decrease dark noise and increase intrascene dynamic range. Most of this improvement can be achieved with thermoelectric cooling to 32°F, although this is heavily device-dependent. Dynamic range increases by at most a factor of three, allowing sensor operation in deep twilight.

B. Attenuation

On a clear day with the sun directly overhead, scene illuminations can reach 10,000 lumens/ft^2. Therefore light attenuation in the optical system is a necessity in order to avoid total saturation of the sensor. Possible ways to accomplish this attenuation include mechanical auto-iris diaphragms,

electrooptic polarization rotation shutters or liquid crystal light valves. A particularly intriguing implementation of this last device has been patented by NASA[11]. The camera system described uses a liquid crystal light valve to selectively attenuate high-intensity areas of an image while passing low intensity areas. The resulting compression of scene dynamic range allows intrascene dynamic ranges of up to 100,000:1. This form of camera also suggests the use of an image intensifier before the sensor to extend the usefulness of the system.

An area open for further exploration is the feasibility of using a liquid crystal light valve for both attenuation and intensification. The light valve conceptually consists of a photocathode that generates local electric fields as a function of incident light intensity. These fields in turn cause the crystals to rotate the polarization of light transmitted through them. Using polarizers, it is then possible to generate an image from a secondary light source that can be intensity-controlled for optimal light levels to the sensor. Investigations of this technique are planned.

VII. PROOF OF PRINCIPLE

The basic concept, including synchronization of the image to the muzzle motion and the survivability of the optics to gun muzzle environments, was demonstrated in the in door firing range at the BRL.

A. Test of Synchronization Principle

On 23 April, 1984, the synchronization principle was physically simulated at the BRL in the Interior Ballistic Division Indoor Range Facility and is recorded in Ballistic Research Laboratory Notebook No. 24.[14] Figure 17 shows a schematic of the apparatus.

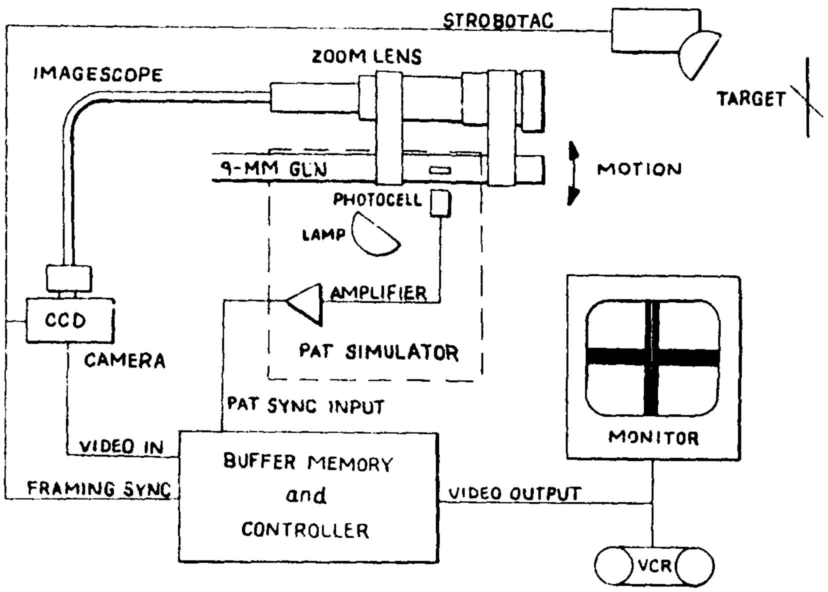


Figure 17. System Used to Physically Simulate PIMS Concept

The following is the list of equipment used to physically simulate the concept.

1. **Gun and Mount.** The tests were performed on a laboratory oscillating gun mount equipped with a 9-mm gun barrel/receiver assembly.

2. **Muzzle Telescope.** The muzzle telescope was simulated using a Minolta TV Zoom Lens Rokkar 4Vx20, 1:2.6 f=20-80 mm.

3. **Imagescope.** A laboratory imagescope with 4-mm hexagonal cross section and 1 meter length was used for the fiberoptic bundle.

4. **Camera.** The camera used in these tests was mounted on a standard tripod separate from the gun and coupled to the muzzle telescope through the imagescope. The camera was a GE CID Camera Model No. TN2500 with a 25-mm Comutar f1.4 lens. Since this camera did not have an exposure control, a strobe light which was synchronized with the camera framing pulse was used to illuminate the target. This was done to minimize blurring in each frame.

5. **Camera Controller.** The camera was controlled by a GE Buffer Memory, Model No. PN2150. The control section of the buffer memory provided the camera and monitor framing pulses. The buffer memory stored the image each time it received a synchronization pulse from the PAT simulation system.

6. **Image Recorder.** The image transmitted to the monitor was recorded through a "T" connector by a Video Cassette Recorder Panasonic Model No. PV-5000.

7. **Monitor.** The image was displayed on a monochromatic monitor, Sony Model No. CVM 950.

8. **Target Illumination.** The strobe light source for the target was a General Radio Strobotac Model Type 1531-A.

9. **PAT Simulator.** The PAT system was simulated by a locally fabricated photodiode and conditioning circuit which monitored illuminated reflective tape positioned on the oscillating gun mount.

This system was able to reduce the motion-induced vertical image jitter by a factor greater than 320:1. The measured image shift was a total of 10 angular mils when unstabilized with a frequency of 2.5 Hz. The apparent shift of the image was 0.03 angular mils when stabilized.

B. Survivability Tests

A telescope was designed with a mounting system for a 37-mm cannon. This system included an 75-mm focal length doublet with field flattener and an 8x10-mm by 1 meter imagescope which had steel braid protection. The scope for these tests did not include thermal compensation. The mount was equipped with removable mechanical filters. These tests were to determine the survivability of the scope and fiberoptics on the muzzle of the gun during firing. The proportions of projectile mass and propellant charge were adjusted to provide a blast and acceleration environment at the muzzle equivalent to that achieved on the M-68 105-mm cannon. The camera, framing and recording system was the

same as previously described. Figure 18 shows the optical components used in these tests.

There was no discernible damage to the optics or degradation of performance before and after the test shots. The isolation characteristics of the mechanical filters appeared to be linear low pass with a cut-off frequency of 900 Hz. These tests were performed and completed on 25 July 1985[15].

VIII. EXTENDED APPLICATIONS

The PIMS system requires the use of new technologies which can be utilized for other fire control related tasks such as ranging, tracking, or enhanced imaging and cueing. The resulting data made available by such a system can also be used in other tactical systems such as APS, fire control, C^3I, and the Weapon System Executive.

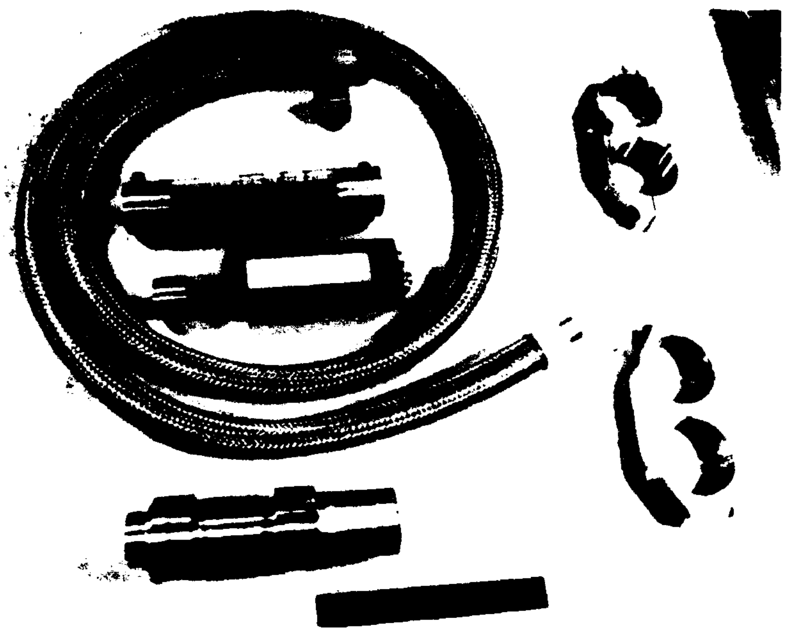


Figure 18. Optical Components Used in Survivability Tests

A. Passive Ranging

If a second, identical telescope and imagescope are attached to the opposite side of the muzzle, the redundancy of systems results in a reduction of vulnerability. In addition, since the two telescopes are separated by a fixed distance, ranging by optical parallax is possible. In practice, only a single line of the image (i.e. the one under the horizontal cross hair) is needed. When the same line is extracted from the images and focused end to end onto a single linear sensor, the parallax can be measured electronically. The optics are designed to present only the preselected areas of the images to their respective regions of the sensor. The processing to extract the parallax measurement from the linear images can be accomplished by performing a digital image correlation between the two sets of 64 points. This function can be readily implemented by available digital signal processors. The range can be determined from the following relationship:

$$R = L * Fl / D \quad (9)$$

where

L = length between the centers of the optical telescopes;
Fl = focal length of the optical system; and
D = displacement between images

Since the active areas of the optical sensor are finite in size (typically 10 microns center-to-center) overall system magnifications of 30X are required in order to obtain reasonable range resolution within 3 km.

B. Autotracking

The availability of high framing rates and the ability to store successive frames of image data greatly reduces the computational burden involved with autotracking techniques. Because of the high frame rate a moving target does not leave the field of view within one frame interval. Since it is necessary to use a search algorithm to find a designated target in subsequent frames, smaller displacements of the target between frames greatly enhance the speed and ability of the algorithm to follow the target. The smaller these displacements become, the simpler and more reliable the algorithm becomes.

C. Image Enhancement

The recommended ping-pong frame buffer system can perform successive differences or filterings of the image data. This capability facilitates the use of image enhancement techniques such as edge sharpening, fog and haze reduction, contrast tailoring, and non-linear filtering for noise reduction.

D. Multisensor Image Fusion

A salient feature of the fiberoptic transmission link is its ability to transmit light ranging from the near-IR (1200 nm) to the near-UV (300 nm). Sensors with different spectral ranges may thus view the same image simultaneously, and their output fused in a single image. The addition of IR imaging to the gunner's sights allows visual acquisition of laser system outputs; UV imaging allows enhances detection of gun flash and missile plumes. (With the addition of an image intensifier, night vision is also made available to the gunner).

E. Other Battlefield Systems

The PIMS concept was developed to address the direct fire problem from a moving platform and is not restricted to tank systems. By varying component parameters within the PIMS system, the concept can be used as the primary sensor for battlefield surveillance and reconnaissance systems. With the high frame rates available, it is conceivable that low flying, high speed aircraft could be successfully tracked and appropriate engagement intercepts computed.

IX. SUMMARY

A. Major Advantages

The demonstrated major advantages of the PIMS concept are summarized as follows:

1. The system is expected to reduce the effect of variable jump by 50%.

2. The system eliminates the need for a servo link between the sight and the gun.

3. The dynamic pointing direction of the gun system is not necessarily the muzzle[16,17]. The system can be made to point the gun from the optimum position along the barrel.

4. The system synchronizes the sight image with the optimum tube condition for projectile launch.

5. The system provides a technology basis for passive ranging, autotracking, and image enhancement.

6. Extension of system principles can be applied to similar tasks in automated systems such as APS, C^3I and robotic systems.

B. Technology Requirements

This work has uncovered several areas of technology that still need aggressive pursuit in development and producibility. These areas include:

1. Compact, high speed solid state image sensors with resolutions of 1024 x 1024, dynamic ranges of 5000:1, and frame rates of 1000/sec or greater.

2. Long (about 10m), low loss imagescopes with resolutions of 50 line pairs/mm, active areas of 1 cm^2, attenuation of 50 dB/km over a spectral range of 250 nm to 2000 nm, and capability to withstand the blast environment.

3. Electronically tunable non-polarizing neutral density filters, with transmissions from 95% down to 0.1%.

4. High light level output image intensifiers capable of gains to 10000 and output light levels of 50 fc.

5. High-speed, flexible, parallel-architecture tactical computers capable of image processing tasks.

The PIMS concept outlined in this report offers a major advance in the state of the art in large gun aiming systems. In addition to significant increases in performance and reduction of both errors and system complexity, it can be expected to provide a reduction in system cost.

ACKNOWLEDGEMENTS

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